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Title: Study on Locally Confined Deposition of Si Nanocrystals in High-Aspect-Ratio Si Nano-Pillar Array for Nano-Electronic and Nano-Photonic Applications"

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Abstract:

In this project, versatile processing techniques are established for improving the internal and external quantum efficiencies of Si MOSLEDs via the detuning the size and density of high-aspect-ration Si nano-rod and buried Si nanospheres. A rapid thermal annealing synthesis of metallic nanodot array is realized to control the size and density control of metallic nanodots as an etching mask for obtaining Si nano-rod or nano-pillars. Afterwards, the induced-couple-power reactive ion etching (ICP-RIE) of metallic nanodot masked Si substrate is performed for high density and aspect-ratio Si nano-pillar array formation. The localized PECVD deposition of Si nanospheres within Si nano-pillar array is achieved under high deposition-temperature and low plasma-power circumstances. The current-voltage, Fowler-Nordheim tunneling, and EL characteristics of the MOS light emitting diodes made on Si nano-pillar roughened p-Si surface is analyzed. Microwatt light emission from MOSLED made by using SiO_x film with buried Si nanocrystals on Si nano-pillar array is demonstrated. The Si nano-pillar array obtained by drying the rapidly self-aggregated Ni nano-dot masked Si substrate exhibit size, aspect ratio, and density of 30 nm, 10, and 2.8×10^{10} cm^{-2}, respectively. These high-aspect-ratio Si nano-pillar array helps to enhance the Fowler-Nordheim tunneling based carrier injection and to facilitate the complete relaxation on total internal reflection, thus increasing the quantum efficiency by one order of magnitude and improving the light extraction from the nano-roughened device surface by three times at least. The light-emission intensity, turn-on current and power-current slope of the MOSLED are 0.2 mW/cm^2, 20-30 μA and 3±0.5 mW/A, respectively. At a biased current of 400 μA, the highest external quantum efficiency is over 0.2% to obtain the maximum EL power of >1 μW. In compared with the same device made on smooth Si substrate under a power conversion ratio of 1×10^{-4}, such a output power performance is enhanced by at least one order-of-magnitude.

Introduction:

This project proposes to study the structural and physical aspects and the specific fabrication techniques in developing versatile Si nano structures, including nanocrystallite Si dot/rod/pillar/pyramid, and nano-Si/metal co-doped mesoporous silica, and self-aggregated noble metal on Si-rich Silica. These novel material systems will be soon applied to different researching fields for comprehensive studies in electronics, photonics and nio-photonics. Three featured subjects are investigated. First of all, a preliminary investigation on the characteristics of high-aspect Si nano-pillar array with a rod size in the quantum confinement regime will be demonstrated, including the photoluminescence, electroluminescence, linear and nonlinear optical coefficiences at visible and near-infrared wavelengths. Such a long Si nano-pillar will be fabricated and geometrically

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14. ABSTRACT
This project established versatile processing techniques for improving the internal and external quantum efficiencies of Si MOSLEDs via detuning the size and density of high-aspect-ratio Si nanorods and buried Si nanospheres.

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controlled to further realize its anamolous dispersion feature and ultra-low reflectivity for potential applications in all-optical switching logic devices and high-efficiency solar cells. Secondly, the l ocally confined deposition of Si nanocrystals in high-aspect-ratio Si nano-pillar array for enhanced quantum efficiency of Si light emitting diodes and solar cells will thus be possibly achieved. The synthesis of buried Si nanospheres in the Si-rich SiO_2 film can considerably be confined within the Si nano-pillar array, in which their spherical diameter will be precisely controlled for fabricating Si nanophotonic devices, such as light emitting and biophotonic sensing devices. The enhanced field emission of such a high-aspect-ratio Si nano-rod and its influence on the one- or two-dimensional carrier transport in a MOSLED structure, and the polariton effect which could be occurred under linearly polarized optical pumping scheme are also intriguing topics to be elucidated. With these novel structures, we propose to study the interfacial tunning or impact ionization mechanism between the Si nano sphere/pillar/rod and adjacent silica/metallic phase, and to investigate the theoretical carrier-phonon interactions between among versatile Si nanostructures and bio-molecules.

In particular, such a novel Si nano-spherie/nano-pillar film structure can be employed to fabricate new Si junction diodes and thin-film-transistors, especially a Si nano-pillar based bio-photonic concentrator for remarking and labeling specific viruses. These investigating results are composed of numerous nano-physical pictures and mechanisms to fulfill our knowledge base at current stage. We expect to realize the physical aspects behind the current injection and recombination, Raman shift, and surface plasma enhancement occurred in the doped nano-Si matrix or between the nano-Si/nano-metal and nano-Si/SiO_2 interfaces through a novel computational model based on *ab initio* atomic potentials by using boundary-integral Green's function method. In particular, the enhanced UV-blue radiation/absorption, the sensitized solar energy conversion, the specific carrier coupling and tunneling phenomena between quantized energy states, and the effect of the quantized three-dimension space charge accumulation can be elicudated in more detail. The contribution of the surface self-confined exciton and the quantum-confined energy levels to the photo- and electro-luminescence from the doped Si nano-pillar based p-n junction diode will be clarified. With the featured infra-structures including the low-power PECVD and laser annealing system for the synthesis of nano-Si or nano-metallic quantum confined structures, the precise and repeatable deposition of Si-rich SiO_x film with controlled composition ratio has been developed to achieve the three-dimensional manipulation and optimization of versatile Si nanostructures such as the Si nano-cluster confined within the silicon nano-rod and the two-dimension Si nano-pyramid. The colorful MOSLEDs covering the UV-blue, green, yellow and red wavelength regions with enhanced light emitting efficiency are demonstrated.

Experiment:

To fabricate a SiO_x based MOSLED on Si nano-pillar array, the Si nano-pillar roughened Si substrate surface is obtained by rapid thermal annealing a 5-nm thick Ni film evaporated on a 20-nm thick SiO_2 layer covered Si substrate to induce self-aggregation of two-dimensional randomized Ni nano-dots mask.[17] Subsequently, a large-area Si nano-pillar array with rod diameter of 30 nm and height of 350 nm can be formatted on Si substrate through the ICP-RIE procedure with such a self-assembled Ni/SiO_2 nano-dots based nano-mask.[18] Afterwards, the Si-rich SiO_x film was deposited on p-type (100)-oriented Si substrate with a Si nano-pillar roughened surface using PECVD with a recipe of SiH_4/N_2O fluence ratio of 1/5, chamber pressure at 60 mtorr, and plasma power of 30 W and substrate temperature of 400^{o}C.[19, 20] After deposition, the Si-rich SiO_x film with thickness of 240 nm was post-annealed in a quartz furnace with flowing N_2 at 1100^{o}C for 60 min to precipitate nc-Si. The size and density estimated from high-resolution TEM are 4±0.5 nm and 2×10^{18} cm^{-3}. The device structure of an ITO/SiO_x/Si/Al MOSLED with buried Si nanocrystals made on silicon nano-pillar array is illustrated in Fig. 1. The MOSLED with a circular contact diameter of 0.8 mm is top bonding by a Cu wire and thermal-electric controlled at bottom side for EL analysis. To confirm the surface roughening effect, the cross-section-view photograph of the Si-rich SiO_x deposited Si nano-pillar surface obtained from secondary electron microscopy (SEM) is shown in Fig. 2.

Results and Discussion:

Plasma enhanced chemical vapor deposition (PECVD) grown Si-rich SiO_2 or SiO_x with embedded Si nanocrystals (referred hereafter as SiO_x:nc-Si) of extremely high density have been extensively investigated as a new class of light emitting material over decades.[1-3] The SiO_x:nc-Si based metal oxide semiconductor light emitting diode (MOSLEDs) is indeed a potential candidate for next-generation optoelectronic applications such as the optical interconnect, the optical communication, and the micro-display panels. The advantages of SiO_x:nc-Si based MOSLEDs include wavelength-tunable and full-color emission, processing compatibility with other MOS devices, system feasibility and low cost of fabrication. Electroluminescence (EL) from the SiO_x:nc-Si film grown by anomalous PECVD recipe has previously been observed [4-8], however, the EL intensity and external quantum efficiency is extremely low due to the nature of indirect recombination, the insulating property of the host oxide, and the tunneling dependent carrier injection. Versatile methods were proposed to improve the efficiency of carrier injection into nc-Si, which include the increasing on density of the nc-Si embedded in SiO_x film, the decreasing thickness of the nc-Si layer and the bandgap engineering of the contact metal. However, an efficient approach to improve the carrier injection into the nc-Si embedded in the SiO_x film via the Si nano-roughened surface based electrode has never reported. Recently, the fabrication of Si nano-pillar array based on the electron-beam (E-beam) lithography and inductively couple-plasma reactive ion etching (ICP-RIE) process were introduced.[9-12] The Si nano-pillar array with its rod size of <10-nm can be re-produced under the control of E-beam lithography.[12] In addition, the self-assembled metallic nano-dots have also emerged to function as nano-sensor for either bio-photonics or etching-mask for nano-electronics. Ni has been considered as an alternative to the other noble metals (Au or Ag) for dry-etching the high-aspect-ratio Si nano-pillars on Si substrate.[12-15] It is thus worthy discussing the external quantum efficiency for light emission from a SiO_x:nc-Si based MOSLED made on such a high-aspect-ratio Si nano-pillar array on Si. In principle, there is an inherent limitation on the quantum efficiency since the light extraction efficiency of most conventional LEDs is limited by the total internal reflection (TIR) of the emitting light from the active region of the LED, which always occurs due to the large difference in the refractive index at the interface between LED top-surface and air.[16] In this letter, we demonstrate a novel SiO_x:nc-Si MOSLED made on the dense Si nano-pillar array to enhance both the carrier injection and light extraction efficiencies, in which the Si nano-pillars is fabricated by reactive-ion etching an oxide-covered Si substrate encapsulated with the self-assembled Ni nano-dot mask. Anomalous photoluminescence (PL) spectra of Si nano-pillars at visible and near-infrared spectral regions are also investigated. Such a Si nano-pillar array is proposed to enable a microwatt power emitting from the SiO_x:nc-Si based MOSLED. The broadband electroluminescent (EL) spectrum and improved turn-on characteristics of such a novel MOSLED, with its external quantum efficiency increasing by enhanced carrier injection and light-extracting mechanisms are reported

1. Enhanced Carrier Injection in the SiO_x Based MOSLED

In Fig. 3, the measured current-voltage response of the ITO/SiO_x:nc-Si/p-Si/Al MOSLED made on Si nano-pillar reveals a significant improvement on its turn-on characteristic as compared to that of the same device made on uniform p-type Si wafer. In general, four possible carrier transport mechanisms can be involved in the MOSLED made by SiO_x with embedded Si nanocrystals, which include the direct tunneling, the Fowler-Nordheim (F-N) tunneling, the thermionic emission and the Poole-Frenkel (P-F) tunneling. The direct tunneling of carriers usually occurs when the applied voltage on the MOSLED structure is relatively smaller than the barrier height of the metal-SiO_x interface, in which electrons can only tunnel through the whole SiO_x film with a thickness of thinner than 5 nm. In contrast, when the applied voltage is equivalent to or larger than the barrier height of the metal-oxide interface, the electrons from the metal side experience a triangular barrier when tunneling into the SiO_x. Such a case is referred to as the Fowler-Nordheim (F-N) tunneling effect. Theoretically, the current density of the direct and F-N tunneling mechanisms (J_{dir} and $J_{F\text{-}N}$) are expressed by [21-23]

$$J_{dir} = \frac{AE_{ox}^2}{\left[1-\sqrt{1-qV_{ox}/\Phi_B}\right]^2}\exp\left(\frac{-B\left[1-\left(1-qV_{ox}/\Phi_B\right)^{1.5}\right]}{E_{ox}}\right) \quad (1)$$

$$J_{FN} = \frac{q^3\left(m/m_{ox}\right)}{8\pi h\Phi_B}E_{ox}^2\exp\left(\frac{-8\pi\sqrt{2m_{ox}\Phi_B^3}}{3qhE_{ox}}\right) \quad (2)$$

$$A = \frac{q^3\left(m/m_{ox}\right)}{8\pi h\Phi_B} = 1.54\times10^{-6}\frac{\left(m/m_{ox}\right)}{\Phi_B}[\frac{A}{V^2}] \quad (3)$$

$$B = \frac{8\pi\sqrt{2m_{ox}\Phi_B^3}}{3qh} = 6.83\times10^7\sqrt{(m_{ox}/m)\Phi_B^3}[\frac{V}{cm}] \quad (4)$$

where q is the electron charge, h is Planck's constant, E_{ox} is the applied electric field on the SiO_x, m_{ox} is the effective electron mass in the SiO_x, m is the free electron mass, Φ_B is the barrier height at the metal-oxide interface, and V_{ox} is the biased voltage across the MOSLED. To realize if F-N tunneling is the dominated mechanism for the carrier transport behavior in the ITO/SiO_x:nc-Si/p-Si/Al MOSLED, the electric field (E) dependent emission current density (J) is also plotted and shown in Fig. 4. A linear $\ln(J/E^2)$ vs. 1/E relationship is observed and the experimental data of the MOSLED can be well fitted by F-N tunneling model as compared to other mechanisms. For example, a simulated direct tunneling current with m_{ox}/m ratio of 0.26, the barrier height of 3.8, the oxide thickness of 2.3 nm is also shown in Fig. 4, which is much larger than the actual currents flowing through the ITO/SiO_x:nc-Si/ p-Si/Al MOSLED. In our case, the direct tunneling current is negligible since the SiO_x thickness is much thicker.

On the other hand, the current density through a metal-semiconductor contact dominated by thermionic emission is also discussed if we consider the Si nanocrystals within in the SiO_x as a possible carrier transport path,[24] which is give by

$$J_{thermionic} = A^*T^2 \exp\left(\frac{-q\Phi_B}{kT}\right)\left(\exp\left(\frac{qV}{kT}\right)-1\right), \quad (5)$$

where $A^* = 4$ pqk^{2}m*/h^3 = 120 (m_{ox}/m), A/ cm^2 K^2 is Richardson's constant, m is free electron mass, m_{ox} is the effective electron mass in SiO_x film, and T is the absolute temperature. By setting m^*/m = 0.26, T = 300 K, and Φ_B = 3.8 eV, a simulated thermionic current is shown in Fig. 4, which is much larger than the measured current of the ITO/SiO_x:nc-Si/ p-Si/Al MOSLED. Therefore, it is impossible to observe thermionic current in the ITO/SiO_x:nc-Si/ p-Si/Al MOSLED. Furthermore, the Si nanocrystals could also be treated as the defects to contribute another carrier transport so-called Poole-Frenkel (P-F) tunneling, which can be evaluated by using the followingexpression [25, 26]

$$J_{PF}(E_{ox},T) = qN_tE_{ox}\mu\exp\left(-\frac{q\Phi_{PF}}{kT}\right)\exp\left(\frac{1}{kT}\sqrt{\frac{qE_{ox}}{(4)\pi\varepsilon_{ox}}}\right) \quad (6)$$

where N_t is the volume density of occupied traps, μ is the carrier mobility, Φ_{PF} is the barrier height for hopping carriers, and ε_{ox} is the permittivity of the SiO_x film. The P-F tunneling and Schottky emission are not differentiated each other by their electric field and temperature dependence, except that a factor 4 presented in the bracket of the field dependent term of Eq. 6 is assumed to be negligible for thick oxide film (>10 nm) in Schottky emission case. In our case, the possible P-F tunneling current is also simulated by using parameters of the ITO/SiO_x:nc-Si/p-Si/Al MOSLEDs such as the electron charge q of 1.6022×10^{-19} C, the estimated volume density (N_t) of 10^{18} cm^{-3}, the carrier mobility μ of 20 cm^2/V sec at 300 K, the thermal energy kT of 0.02586 eV at 300 K, the barrier height Φ_{PF} of 1.37 eV, and the permittivity of SiO_x film ε_{ox} of 3.24 ($\varepsilon_{ox} = n^2 = 1.8^2$, where n is refractive index of the SiO_x film), which has therefore been addressed as a less pronounced mechanism as compared to the F-N tunneling effect.

From these theoretical analyses, it is confirmed that the light emission from the SiO_x based MOSLED is indeed based on the electron-hole recombination in the Si nanocrystals, in which the electrons and holes are tunneling through ITO-SiO_x and Si-SiO_x barriers, respectively.[27-30] Originally, the F-N tunneling effect also occurs in the MOSLED sample made on a smooth Si wafer without Si nano-pillars, however, which suffers from insufficient large tunneling carriers tunneled through the oxide structure and injected into the Si nanocrystals. The corresponding band diagram of the MOSLED for explaining the Si-nanopillar enhanced F-N tunneling effect is shown in Fig. 5, which indicates either the reduced size of Si nanocrystal or decreased barrier height at SiO_x-Si and metal-SiO_x interfaces can provide such MOSLED an exceptionally high EL output. This has also been concluded from our experimental result and the fitting of Fowler-Nordeim tunneling process. In particular, the effective barrier height for carriers at the junction interfaces of the MOSLED can further be greatly reduced due to both the synthesis of Si nanocrystals and the formation of Si nano-pillars, as shown in Fig. 5. Similar report were addressed by Prakash and co-workers.[31] The existence of Si nano-pillars facilitate the growth of Si-rich SiO_2 with well size-controlled Si nanocrystals in between, in which the effective barrier height at the Si-SiO_2 interface reduces to cause the shrinkage of the tunneling distance of the oxide triangular barrier between metal/p-Si and Si nanocrystals. Therefore, both the densities of electrons and holes injected into the Si nanocrystals can be significantly increased due to such a hybrid Si nano-pillar array and Si-rich SiO_x structure.

As a result, the carrier recombination process is greatly enhanced due to the increasing carriers injected into the Si nanocrystals, which essentially gives rise to an improved EL performance and an enlarged light emitting power.

2. Enhancement on Light Extraction of SiO_x Based MOSLED

Under a bias of 100 mA, the EL spectrum of the MOSLED is compared with its PL spectrum and shown in Fig. 6. The EL and PL is alike each other except the enhanced part on the short-wavelength region contributed by the small-size Si nanocrystals. Such a difference is attributed to the higher carrier tunneling probability of carriers to the Si nanocrystals with smaller sizes. In addition, it may partially arises from the consecutive hot-carrier injection from one Si nanocrystal to another, leading to a higher probability of recombination at the higher quantized states of the Si nanocrystals. In principle, there are two principal approaches for improving the LED efficiency: the first is increasing the internal quantum efficiency, which is determined by crystal quality and epitaxial layer structure, and the second is increasing light extraction efficiency. Roughening the top surface of an LED is one of the methods for improving the light extraction. The roughened top surface reduces internal light reflection and scatters the light outward. In our case, the light-extraction efficiency of the SiO_x based MOSLED with buried Si nanocrystals is limited mainly due to the large difference in the refractive index between the nc-Si film and surrounding air. The critical angle determined by Snell's law, that is, the angle that the photons can escape from the nc-Si layer to air, is crucially important to improve the light-extraction efficiency of the nc-Si based MOSLED. The key to enhance the escape probability of light is to give the photons generated in the active layer of the nc-Si based MOSLED structure multiple opportunities to find the escape cone. Our device structure shown in Fig. 1 exactly meet the demand on angular randomization or scrambling of the photons, which is the concept of our design by using the Si nano-pillar array to achieve such a purpose. Figure 7(a) shows the possible photon paths at the interface between the nc-Si layer and surrounding air for nc-Si based MOSLEDs without surface roughening. For a nc-Si based MOSLED with a nc-Si top surface which was roughened, the angular randomization of photons can be achieved by surface scattering from the roughened top surface of the MOSLED, as shown in Fig. 7(b). Thus, the roughened surface structure can improve the probability of escaping the photons outside from the nc-Si based MOSLED, resulting in an increase in the light-out power of MOSLED, as shown in Fig. 8. However, there are still different P-I characteristics among samples even the Si nano-pillar array are fabricated on same wafer at once. The maximum output power of the SiO_x based MOSLED made on the Si nano-pillar can be increase by almost one order of magnitude higher than that of the same device made on an uniform Si wafer. The maximum optical output power, biased current, biased voltage and external quantum efficiency are 1 μW at biased current and voltage of 0.4 μA and 36 V, respectively. The peak wavelength and electrical to optical power conversion ratio of the SiO_x based MOSLED with Si nano-pillars are 0.76 μm and about 1×10^{-4}, respectively.

For an nc-Si based MOSLEDs, the refractive indexes of nc-Si ($n_{nc\text{-}Si}$) and the air (n_{air}) are 1.8 and 1, respectively. In this case, the critical angle (θ_c= sin-1 $n_{air}/n_{nc\text{-}Si}$) for the light generated in the active region to escape is about 33.7°. Assuming the light emission from the active region of an nc-Si based MOSLED is isotropic and the light can escape from the chip if the angle of incidence to the chip wall is less than the critical angle, a small fraction of light generated in the active region of the nc-Si based MOSLED can escape to the surrounding air. In our MOSLED device, the output power is uniformly distributed over the whole half-spherical surface with a full solid angle of $\Omega_{half} = 2\pi$, the emitting solid angle of the MOSLED limited by the total internal reflection (Ω_{TIR}) is 0.34π. Assuming the maximum power can be emitted is P, the output power can be emitted from the MOSLED without the limitation of the total internal reflection is $P \times(\Omega_{TIR} / \Omega_{half}) = 0.17P$. Only a small fraction of light (about 17%) can escape from the nc-Si based MOSLED even though the refractive index of the top ITO contact layer is nearly the same with the Si-rich SiO_x film to prevent additional reflection. Therefore, for a conventional nc-Si based LED, the external quantum efficiency limits to a few percent due to the high refractive index of nc-Si as well as the absorption in the metal pad for current injection and free carriers, even if the internal quantum efficiency close to 100% is reached. The improvement on light-extraction efficiency of the nc-Si based MOSLED relies on the angular randomization or scrambling of the photons via surface roughening effect. The comparison on the nc-Si based MOSLED made on Si nano-pillar array and smooth Si substrates under the same biased current of 150 μA clearly shows an increase on output EL power by a 3.8 times, as shown in Fig. 9.

The power enhancing factor of our devices is better than those ever reported on the other LED devices based on compound semiconductor material. Previously, the surface roughening induced EL power enhancement on GaN- or InGaN-based LEDs has been reported.[32-34] In particular, Fujii et al. [16] have reported the output power of a GaN-based LED made on optimally roughened surface, which shows a two- or three-fold enhancement as compared to that of a GaN-based LED made on the substrate without surface roughening. Huang et al. [15] have also demonstrated the emitting power and wall-plug efficiency of aInGaN–GaN LED with a nano-roughened top p-GaN surface can be improved by 1.4-time and 45% higher than that of a conventional LED with top-surface roughening process. In comparison, our experiments conclude that the Si nano-pillar array improves not only the carrier tunneling but also the light extraction in the nc-Si MOSLED. Obviously, the nano-roughening top surface of the SiO_x MOSLED is also one of the efficient methods for increasing the light extraction rate to improve the external quantum efficiency of the LED. If we define the external quantum efficiency as the ratio of the output photo number and input electron number described by the equation below,

$$\eta = \frac{\int_{t_0}^{t_1} P_{opt} \times t\,dt \Big/ \frac{1.24}{\lambda} \times 1.6 \times 10^{-19}}{\int_{t_0}^{t_1} I \times t\,dt \Big/ 1.6 \times 10^{-19}} = \frac{P_{opt}}{I \times (1.24/\lambda)}, \qquad (7)$$

where P_{opt} is optical output power, t is experimental duration, λ is wavelength, I is biased current. The highest external quantum efficiency obtained from our SiO_x based MOSLED on Si nano-pillar is up to 2×10^{-3}, which is mainly attributed to the enhanced carrier transport through the nano-tip structure. Note that internal quantum efficiency contributed by the buried Si nanocrystals within the SiO_x based MOSLED made on Si nano-pillars could be much larger than the external quantum efficiency. The PECVD growth of SiO_x on the Si nano-pillar array can also help to confine the size and thus promote the density of Si nanocrystals among the Si nano-pillars. Further improvement on the light emitting power and external quantum efficiency relies on the optimization of both the height and aspect ratio of Si nano-pillars, which helps to enhance the F-N tunneling based carrier injection and to facilitate the complete relaxation on the total internal reflection at the MOSLED top surface.

In conclusion, we have demonstrated the MOSLED made by SiO_x with buried Si nanocrystals on Si nano-pillar array to enable microwatt light emitting power. The Si nano-pillar array on Si substrate is fabricated by using the rapidly self-aggregated Ni nano-dots on Si substrate covered with a thin SiO_2 buffered layer as an etching mask, while the Ni nano-dots can be formatted after rapid thermal annealing at 850 °C for 22 s with size and density of 30 nm and 2.8×10^{10} cm^{-2}, respectively. The Si nano-pillar array with aspect ratio as high as 10 can be obtained after dry-etvhing the Ni nano-dot masked Si substrate surface. The EL performance of the SiO_x based MOSLED with buried Si nanocrystals made on such high-aspect-ratio Si nano-pillars is greatly enhanced. The emitting optical intensity, turn-on current and power-current slope of the MOSLED are 0.2 mW/cm^2, 20-30 μA and 3±0.5 mW/A, respectively. The highest external quantum efficiency is exceeding 0.2% to provide maximum EL power of >1 μW at biased current of 400 μA, and the EL power is already improved by one order of magnitude as those obtained from similar devices made on the smooth Si wafer under a power conversion ratio of 1×10^{-4}. The reduction of turn-on threshold voltage and the enhancement on Fowler-Nordheim tunneling performances of the nc-Si based MOSLED made on Si nano-pillar array essentially raise the possibility of its EL power toward 10s-μW regime.

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Figure Captions

Fig. 1 Device structure of a silicon nanocrystal based MOSLED on silicon nanopillar array.

Fig. 2 SEM cross-section view photograph of the SiO_x on Si nano-pillar array.

Fig. 3 Current-voltage response of the SiO_x based MOSLED made on Si nano-pillar array (red circle) and uniform Si substrate (blue square).

Fig. 4 The MOSLED current contributed by versatile carrier tunneling mechanisms. (a) Direct tunneling current, (b) Fowler-Nordheim tunneling current of SiO_x MOSLED on Si nano-pillar, (c) Poole-Frankel tunneling current, (d) Fowler-Nordheim tunneling current of SiO_x MOSLED on uniform Si substrate, and (e) thermionic emission current. The green dashed line illustrate the fitting curve from the theoretical F-N tunneling model.

Fig. 5 Band diagram of MOSLED on Si substrate under positively biased condition.

Fig. 6 The EL (solid line) and PL (dashed line) spectra of SiO_x based MOSLED.

Fig. 7 Schematic illustration of light emitting paths from the SiO_x based MOSLEDs made on uniform Si aubstrate (upper) and Si nano-pillar array (lower).

Fig. 7 Optical output power as a function of biased current for the SiO_x based MOSLEDs made on Si nano-pillar array and uniform Si aubstrate.

Fig. 8 The power enhance factor of the SiO_x based MOSLED made on Si nano-pillar at different biased currents.

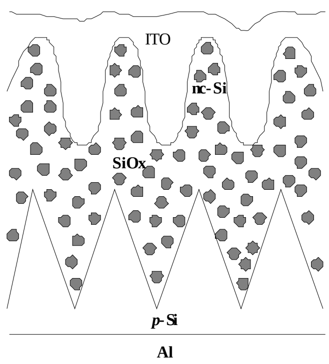


Fig. 1

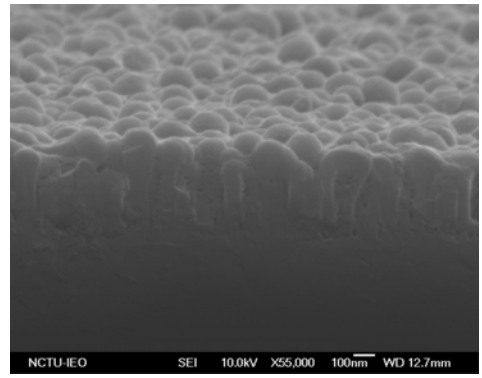


Fig.2

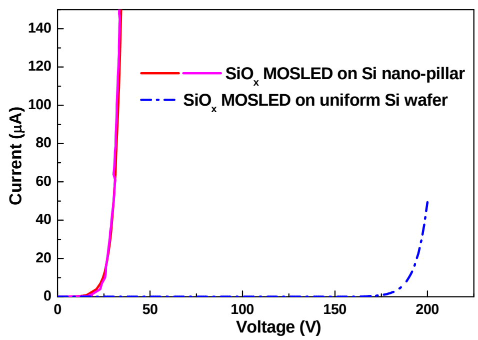


Fig. 3

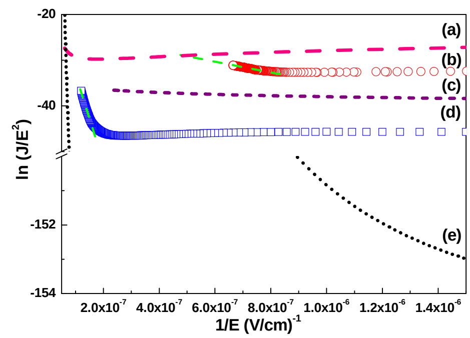


Fig. 4

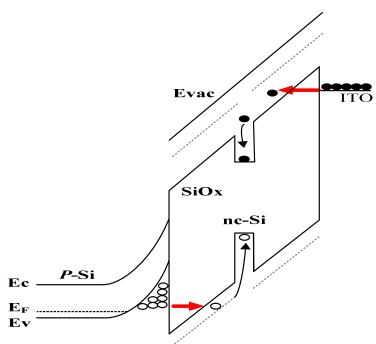
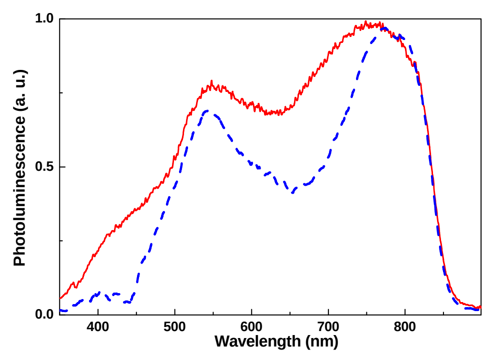


Fig. 5



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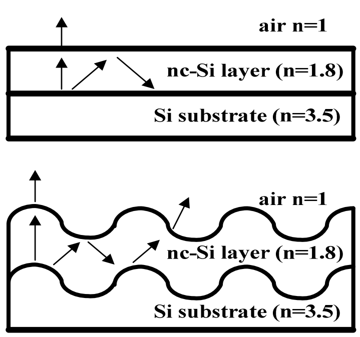

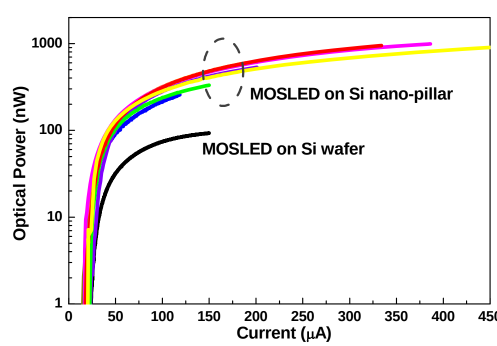

Fig. 7

Fig. 8

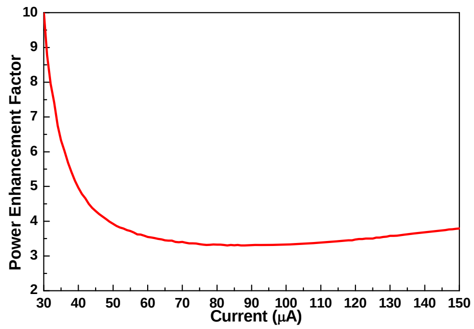

Fig. 9

List of Publications:

Journals

1. Gong-Ru Lin, Fan-Shuen Meng, and Yi-Hao Pai, "Manipulative Depolarization and Reflectance Spectra of Morphologically Controlled Nano-pillars and Nano-rods", ***Optics Express,*** Vol. 17, Issue 23, pp.20824-20832, Oct. 2009.
2. Yi-Hao Pai, Chung-Hsiang Chang, and Gong-Ru Lin, "Composition Optimization and Phase Transformation of Si Nanocrystal Doped SiO_x for Enhancing Luminescence from MOSLED", ***Journal of Selected Topics in Quantum Electronics***, Vol. 15, Issue 5, pp. 1387-1392, Sept.-Oct. 2009.
3. Gong-Ru Lin, Chung-Lun Wu, Cheng-Wei Lian, and Hung-Chun Chang, "Saturated small-signal gain of Si Quantum Dots embedded in $SiO_2/SiO_x/SiO_2$ strip-loaded waveguide amplifier made on Quartz", ***Applied Physics Letter***, Vol. 95, No. 2, 021106, Jul. 2009.
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5. Yi-Hao Pai, Fan-Shuen Meng, Chun-Jung Lin, Hao-Chung Kuo, Shih-Hsin Hsu, Yia-Chung Chang, and Gong-Ru Lin, "Aspect-ratio-dependent ultra-low reflection and luminescence of dry-etched Si nanopillars on Si substrate," ***Nanotechnology***, Vol. 20, No. 3, Jan. 2009
6. Gong-Ru Lin, Yi-Hao Pai, and Cheng-Tao Lin, "Microwatt MOSLED Using SiO_x With Buried Si Nanocrystals on Si Nano-Pillar Array", ***Journal of Lightwave Technology***, Vol. 6, No. 11, pp. 1486-1491, May-June 2008.
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9. Gong-Ru Lin, "Enabling light emission from Si based MOSLED on surface nano-roughened Si substrate", **Invited Paper**, ***IEICE Transactions on Electronics***, Vol. E91C, No. 2, pp. 173-180, Feb. 2008.

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2. Chun-Chieh Chen, Cheng-Tao Lin, Yi-Hao Pai, and Gong-Ru Lin, "Comparison of MISLEDs made on Si-rich SiOx and SiNx", ***2009 Material Research Society Fall Meeting (MRS Fall 2009)***, Poster paper. 674065, Boston, M.A, U.S.A., Nov. 30 - Dec. 5, 2009.

3. Tzu-Chieh Lo, Chun-Chieh Chen, Chih-Hsien Cheng, and Gong-Ru Lin, "Annealing Temperature Dependent Self-organized Silicon Nanocrystal precipitation in Silicon-rich Silicon Carbide", ***2009 Material Research Society Fall Meeting (MRS Fall 2009)***, Oral paper. 673961, Boston, M.A, U.SA., Nov. 30 - Dec. 5, 2009.
4. Chih-Hsien Cheng, Bo-Han Lai, and Gong-Ru Lin, "Red-green-blue MOSLED made by PECVD grown SiO_x with detuning RF plasma power", ***2009 Material Research Society Fall Meeting (MRS Fall 2009)***, Oral paper. 673451, Boston, M.A, U.SA., Nov. 30 - Dec. 5, 2009.
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6. Wei-Lun Hsu, Yi-Hao Pai, and Gong-Ru Lin, "Low Temperature Synthesis of Silicon Nanocrystals in Porous Anodic Aluminum Oxide Substrate", ***2009 Material Research Society Spring Meeting (MRS Spring 2009)***, Poster 578923, San Francisco, C.A., Apr. 13-17, 2009.
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12. Chung-Hsiang Chang and Gong-Ru Lin, "Blue and yellow electroluminescence of MOSLED made on Si-rich SiOx grown by PECVD with detuning buried Si nanoclusters size", ***Conference on Lasers and Electro-Optics (CLEO/QELS 2007)***, Oral paper JThA96, San Jose, California, May 4-9, 2008.
13. Chung-Hsiang Chang and Gong-Ru Lin, "Optimized O/Si Composition Ratio for Enhancing Si Nanocrystal Based Luminescence in Si-rich SiO_x Grown by PECVD with Argon Diluted SiH_4", ***2008 Materials Research Society Spring Meeting (2008 MRS Spring Meeting)***, San Francisco, California, March 24-28, 2008.
14. Bo-Han Lai and Gong-Ru Lin, "Emission wavelength control of Si-rich SiOx MOSLED by detuning vapor fluence and plasma power during PECVD growth", ***2008 Materials Research Society Spring Meeting (2008 MRS Spring Meeting)***, post paper I10.20, San Francisco, California, March 24-28, 2008.
15. Cheng-Wei Lian, and Gong-Ru Lin, "A Buried Silicon Nanocrystals Based High Gain Coefficient $SiO_2/SiO_X/SiO_2$ Strip-Loaded Waveguide Amplifier on Quartz Substrate", ***2008 Materials Research Society Spring Meeting (2008 MRS Spring Meeting)***, oral paper K5.2, San Francisco, California, March 24-28, 2008.
16. Chung-Hsiang Chang, Chin-Hua Hsieh, Li-Jen Chou, and Gong-Ru Lin, "Blue and Yellow Electroluminescence of MOSLED Made on Si-rich SiO_x Film with Detuning Buried Si Nanoclusters Size", ***2008 Materials Research Society Spring Meeting (2008 MRS Spring Meeting)***, Symposium A, Oral Paper 423916, San Francisco, California, March 24-28, 2008.